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Research Article

The COVID-19 Pandemic Waves: Comparative and Statistical Analysis of Their Dynamics

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Abstract

Record numbers of new COVID-19 cases and deaths registered in Japan and European countries in early 2022 aroused new questions about methods of overcoming the pandemic. The pandemic waves in Japan, Ukraine, USA, and Hong Kong in 2020, 2021, 2022 will be compared. Possible influence of testing and vaccination levels will be investigated.

Implications for Public Health.

Increasing the level of testing and adhering to quarantine restrictions for the entire population, including vaccinated people, can be recommended to reduce the negative consequences of the COVID-19 pandemic.

Keywords: COVID-19 pandemic; efficiency of vaccinations; testing efficacy; mathematical modeling of infection diseases; statistical methods

Introduction

The first studies of the effectiveness of SARS-CoV-2 testing appeared in 2020 immediately after the pandemic outbreak (see, e.g., [1–15]). The effectiveness of testing and isolation in reducing the basic reproduction number was investigated in recent paper [14] based on mathematical modeling.

In 2021, with the advent of a sufficient number of vaccinated people, it became possible to study the impact of vaccination levels on the COVID-19 pandemic dynamics (see, e.g. [15–21]). Constant changes in its dynamics caused by changes in quarantine conditions and algorithms for testing and vaccination, the emergence of new strains require updating and rethinking the results of previous studies. To compare the pandemic situation in different countries with different sizes of their population the relative characteristics can be used: e.g., the daily numbers of new COVID-19 cases per million (DCC), deaths per million (DDC), and tests per thousand (TC).

Usually the values of DCC, DDC and TC are very random and show some weekly periodicity. For example, COVID-19 Data Repository by the Center for Systems Science and Engineering (CSSE) at Johns Hopkins University (JHU) provides the daily figures of DCC, DDC, TC and calculates also their smoothed values by averaging numbers corresponding to a fixed day and six previous days [22]. We will take these values for our analysis without using the smoothing procedure proposed in [23]. Since we are already in the fouth year of the pandemic, it is reasonable to compare the values of DCC, DDC and the case fatality risk CFR = DDC/DCC in 2020, 2021, and 2022 in order to find some seasonal trends. Since the influence of vaccinations in 2020 and early 2021 can be neglected, the comparison of the COVID-19 pandemic dynamics for the later period enables us to reveal some influences of vaccination levels. In [24] the DCC values for Argentina, Brazil, India, South Africa, Ukraine, EU, the UK, USA and the whole world for the period from March to August 2020 were compared with the corresponding values in 2021. The DCC, DDC, CFR values and vaccination levels in the same countries and Australia have been compared for the period from September to January in 2020–2021 and 2021–2022, [18]. In this paper we will focus on the DCC, DDC, CFR values registered in Japan in 2020, 2021, 2022 and will try to find their links with the percentage of fully vaccinated people (VC) and boosters (BC), the daily numbers of tests per thousand TC and the daily tests per case ratio DTC = 1000*TC/DCC. The pandemic dynamics in Japan, Ukraine, USA, and Hong Kong will be compared. The non-linear regression will be applied to find links between the DCC and DTC values.

Methods

The smoothed daily numbers of new cases and deaths per capita, the ratio of these characteristics and the non-linear correlation with the tests per case ratio were used. We will use the smoothed daily numbers of new cases (DCC, per million), deaths (DDC, per million) and tests (TC, per thousand) registered by JHU, [22] in 2020, 2021 and 2022. We will also use the accumulated percentages of fully vaccinated persons (VC, in 2021 and 2022) and booster doses of vaccines (BC, in 2022) listed in [22]. Since JHU often updates its data sets, we will specify the versions of its file used in different cases.

To find links between DCC values and the daily tests per case ratio DTC = 1000*TC/DCC we will use the non-linear correlation, [20]:

$$DCC = a + b(DTC + c)^{\gamma}$$

At =1 relationship (1) reduces to a linear one and can be rewritten as follows:

$$z \equiv \log\left(DCC - a\right) = \log(b) + \gamma \log(DTC + c) \qquad (2)$$

Then for new random variables z and we will have a linear regression. The constant parameters, and corresponding best fitting lines can be found with the use of standard formulas for the linear regression [25] for every fixed value of constant parameters a and c.

We will use also the F-test for the null hypothesis that says that the proposed linear relationship (2) fits the data sets. The experimental values of the Fisher function can be calculated with the use of the formula:

$$F = \frac{r^2(n-m)}{(1-r^2)(m-1)} \qquad (3)$$

where n is the number of observations (number of countries and regions taken for statistical analysis); m=2 is the number of parameters in the regression equation, [25]. The corresponding experimental values F have to be compared with the critical values $F_C(k_1, k_2)$ of the Fisher function at a desired significance or confidence level ($k_1 = m-1$, $k_2 = n-m$, see, e.g., [26]). If $F/F_C(k_1, k_2) < 1$, the null hypothesis is not supported by the results of observations. The highest values of $F/F_C(k_1, k_2)$ correspond to the most reliable hypotheses (see, e.g., [23, 27]). In the case of non-linear regression (2) the values of additional parameters a and c must be chosen in order to ensure the maximum of the correlation coefficient r or the highest values of $F/F_C(k_1, k_2)$ (similar to the parameter identification methods used in [23]).

Results.

As in other countries, the deaths per case ratio in Japan decreases with the increase of the vaccination level despite increasing daily numbers cases and deaths.

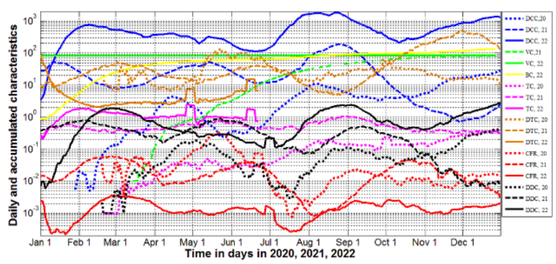

Figure 1: Pandemic dynamics in Japan in 2020, 2021, and 2022. Averaged daily number of new cases per million (DCC, blue lines), deaths per million (DDC, black lines), tests per thousand (TC, magenta lines), vaccination levels (VC and BC, green and yellow lines, respectively), daily tests per case ratio (DTC=1000*TC/DCC, brown lines), and case fatality risk CFR=DDC/DCC (red lines).

Dotted lines correspond to 2020, dashed lines – to 2021 and solid lines - to 2022.Similar pandemic waves caused by the Omicron strain were registered in January 2022 in the highly vaccinated UK, USA and EU (see, e.g., [19]). Moreover, a simple statistical analysis (based on the JHU datasets corresponding to February 1, 2022) revealed the increase in DCC values with the growth of the percentage of fully vaccinated people in European countries and worldwide [20]. The same analysis based JHU datasets reported on September 1, 2021 revealed no statistically significant correlation between DCC and VC values, [21]. These changes in the influence of vaccination level can be explained by lifting the quarantine restrictions for vaccinated people in European countries and USA.

Japan does not reduce quarantine restrictions for vaccinated people inside the country, but all people entering the country have to be vaccinated. Therefore, it is very interesting to investigate the impact of the vaccination level on the daily number of new cases in Japan. Dashed blue and green lines in Fig. 1 demonstrate that daily number of new cases diminished with the increase of the vaccination level in September-December 2021. But the trend has changed in 2022 (compare solid blue and green lines). Figure 2 represent the DCC (blue), DDC (black) and CFR (red) values versus vaccination levels VC ("circles" in 2021 and "crosses" in 2022) and BC (2022, "triangles"). Sharp increase of smoothed daily numbers new cases in 2022 is visible in Figs. 1 and 2 despite very high vaccination level VC. DCC values depend on the percentage of boosters in a wave-like manner, but in the second half of 2022 the number of cases increased with the growth of BC (see blue "triangles" in Fig. 2). Thus, the epidemic dynamics in Japan demonstrated ones more that it is impossible to stop the COVID-19 pandemic with the use of vaccination only [28].

Nevertheless, vaccination can reduce mortality. The decrease of DDC and DDC/DCC values with the growth of VC was demonstrated for European countries by linear regression analysis performed in [20]. In the case of Japan, we see the record increase of daily numbers of deaths DDC in 2022 with the maxima levels corresponding to the end of February and beginning of September 2022 (approximately two weeks later when the maxima of DCC have been achieved, see solid black and blue lines in Fig. 1). Thus, very high VC figures have not reduced daily numbers of deaths in Japan. Comparison of black "circles" and "crosses" in Fig. 2 also supports this conclusion.

The dynamics of the case fatality risk CFR = DDC/DCC in Japan is more similar to the case of European countries. In 2022 it was much lower than in 2021 (compare the solid and dashed red lines in Fig. 1 or red "crosses" and "circles" in Fig. 2). This fact can be related to higher vaccination level in 2022. Nevertheless, very low CFR values were also registered in August 2021 (see the dashed red line in Fig. 1 and red "circles" in Fig. 2) despite the low level of VC. Similar low CFR values were registered also in July 2020 (see the dotted red line in Fig. 1) before starting the vaccinations. We can explain this fact by the influence of the seasonal factors. The probability of deaths caused by SARS-CoV-2 seems to be lower in the summer.

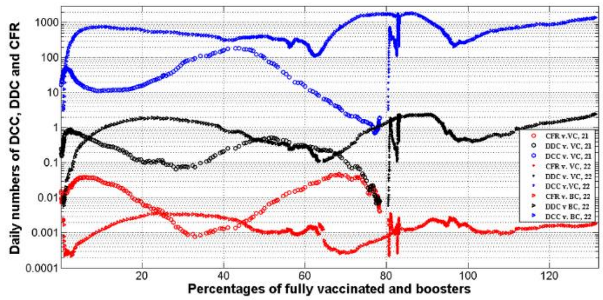

Figure 2: Pandemic dynamics in Japan in 2021 and 2022 versus vaccination levels. Averaged daily number of new cases (DCC, blue), deaths (DDC, black) and case fatality risk (CFR=DDC/DCC, red) versus percentage of fully vaccinated persons ("circles" for 2021, "crosses" for 2022) and versus percentage of boosters ("triangles" for 2022).

The increasing percentage of boosters BC have not reduced the DCC, DDC and CFR values in 2022 (see blue, black and red "triangles" in Fig. 2). As of February 1, 2022, the DCC values increased, but DDC and CFR figures decreased with the growth of BC for European countries, [20]. Since the existing vaccines can reduce only the probability of death for an infected person, of particular relevance is the question of methods that could minimize the number of new cases. Daily numbers of new cases per million versus tests per case ratio are shown in [13] for different countries as of January 17, 2021. Despite the rather chaotic nature of the data, we can see a clear trend of decreasing the number of new cases with an increase in the tests per case ratio. Linear regression analysis applied for the datasets corresponding to European and some other countries (including Japan) as of February 1, 2022 showed that the increase of the tests per case ratio TC = 1000*DTC/DCC reduces the daily numbers of new cases, [20].

Magenta lines in Fig. 1 represent the average daily numbers of tests per thousand TC in Japan listed in [22]. These values were more or less stable in 2021 (see the dashed magenta line). In 2020 the level of testing was much lower (the dotted magenta line), in 2022 it became slightly higher (the solid magenta line). No significant correlations with the daily numbers of new cases (blue lines) are visible.

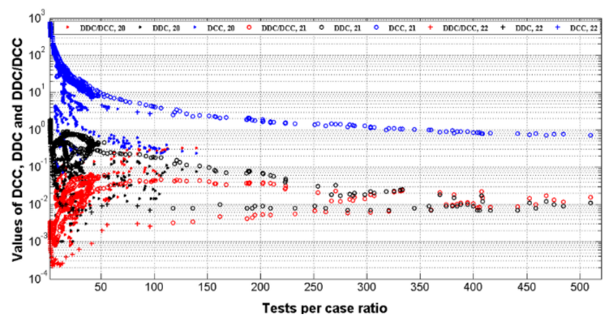

Figure 3: Pandemic dynamics in Japan in 2020, 2021, and 2022 versus daily tests per case ratio. Smoothed daily number of new cases (DCC, blue), deaths (DDC, black) per million and case fatality risk (DDC/DCC, red) versus daily tests per case ratio (DTC=1000*TC/DCC) in 2020 ("triangles"), 2021 ("circles") and 2022 ("crosses").

In comparison, the maximal values of the tests per case ratio DTC = 1000*TC/DCC (see brown lines in Fig. 1) correspond to the minimal figures of DCC (blue curves) and DDC (black ones). Similar correlation was revealed in [13], where the test positivity rate DCC/(1000*TC) (a characteristics inverse to the tests per case ratio) was used. To make these correlations more visible, values of DCC, DDC (version of JHU file published on May 26, 2022, [22]) and CFR = DDC/DCC are plotted versus the daily tests per case ratio DTC in Fig. 3. Blue and black markers illustrate the decreasing of DCC and DDC values with the growth of the tests per case ratio. The DDC/DCC values are more scattered and show no decreasing trend (see red markers).

Year, country	**Number of observations *n***	**Correlation coefficient *r***	**Optimal values of parameter *a* in Eq. (1)**	**Optimal values of parameter *b* in Eq. (1)**	**Optimal values of parameter in Eq. (1)**	**Experimental value of the Fisher function *F*, Eq. (3), *m* = 2**	**Critical value of Fisher function F_c (1, n-2) for the confidence level 0.001, [26]**	**F/F_c**
2020, Japan	**316**	**-0.4956**	**0.45**	**110.7141**	**-1.3457**	**102.24**	**10.8**	**9.47**
2021, Japan	**365**	**-0.9903**	**0.33**	**944.4762**	**-1.2316**	**18431.73**	**10.8**	**1706.6**
2022, Japan	**100**	**-0.9808**	**0.00**	**918.3058**	**-1.2622**	**2483.54**	**11.6**	**214.1**

Year, country	Number of observations n	Correlation coefficient r	Optimal values of parameter a in Eq. (1)	Optimal values of parameter b in Eq. (1)	Optimal values of parameter in Eq. (1)	Experimental value of the Fisher function F, Eq. (3), $m = 2$	Critical value of Fisher function F_c $(1, n-2)$ for the confidence level 0.001, [26]	F/F_c
2020, USA	299	-0.2603	4.14	574.36	-0.6095	21.58	10.8	1.998
2021, USA	365	-0.9642	0.00	10222.8	-1.3957	4796.96	10.8	444.2
2022, USA	95	-0.9962	3.27	5070.4	-1.2371	12328.36	11.6	1062.8

Table 1: Optimal values of parameters in Eq. (1), correlation coefficients and the results of Fisher test applications for Japan and USA in 2020, 2021 and 2022.

We have applied the nonlinear correlation (1) and the version of JHU file published on May 26, 2022, [22] to find the links between DCC values and the daily tests per case ratio. The statistical analysis was performed separately for Japan and USA and for three years: 2020, 2021 and 2022. The results of calculations are shown in Table 1 and Fig. 4. The optimal value of parameter c = − 1 for all cases except the United States in 2022, for which c = -1.09. It can be seen that there are statistically significant correlations for both countries, since

$$F / F_C(k_1, k_2) > 1$$

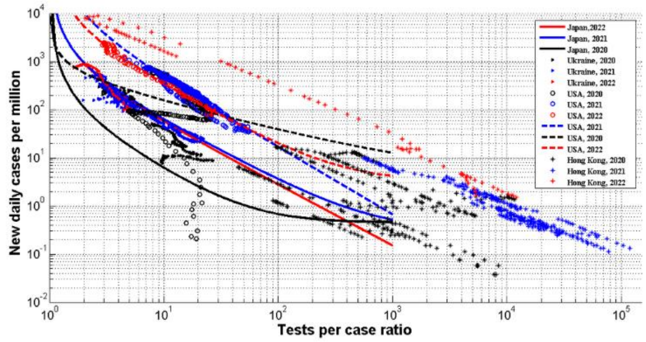

Figure 4: Soothed daily number of new cases per million (DCC) in Japan, Ukraine, USA, and Hong Kong versus daily tests per case ratio (DTC=1000*TC/DCC) in 2020 (black), 2021 (blue) and 2022 (red).

"Triangles" represent the JHU data [22] for Ukraine, "circles" – for USA, "stars" – Hong Kong. The results of non-linear regression (1) are shown by solid best fitting lines for Japan and dashed ones for USA.for all the cases shown in Table 1. Even in 2020 (when the data was rather scattered in Japan, Ukraine, USA, and Hong Kong, see Fig. 4) non-linear correlation (1) was supported by the results of observations at high confidence level 0.001. In 2021 and 2022 the experimental points were very close to the best fifing lines (solid for Japan and dashed for USA). The experimental datasets for Ukraine in 2021 and 2022 are very close to the best fitting lines for Japan in 2021 and 2022 (compare blue and red solid lines with blue and red "triangles" in Fig. 4). In 2020, the number of cases per capita in Ukraine were higher than in Japan at fixed values of the tests per case ratio (compare the black solid line and black triangles in Fig. 4). The number of cases in USA in 2021 and 2022 were approximately 6–8 times higher than in Japan and Ukraine at the same values of the daily tests per case ratio (see Fig. 4). This fact probably reflect the lower level of social distancing in USA.Very interesting is the case of Hong Kong where the very high testing level was supported in 2020 and 2021 (see black and blue "stars" in Fig. 4). Due to this fact the numbers of new cases were less than 2 per million, i.e., the epidemic was controlled completely. The reduce of the tests per case ratio caused a huge epidemic wave with very high DCC values. In particular, the numbers of new cases per capita became even higher than at maximum level in the USA (compare red "stars" and "circles" in Fig. 4). The comparison of the testing levels in Hong Kong at mainland China and their influence on DCC values can be found in [29].

Discussion

Positive values of parameter a in Eq. (1) show that new cases will appear even at very high testing levels, since DCC tends to a as DTC tends to infinity (at negative values of γ). For example, in 2022 the average daily number of new cases per million in USA cannot be less than 3.27 even at very high testing level (see the last row of Table 1). The estimation for Japan is more optimistic, since the best fitting non-linear equation can be written as follows (see Table 1):

$$DCC = \frac{918.3058}{(\mathrm{DTC-1})^{1.2622}}$$

Eq. (4) demonstrates that in 2022 the numbers of new cases in Japan could be reduced to zero at very high testing levels. For example, if the test per case ratio exceeds 500, the average daily number of new cases per million in Japan could be less than 0.36. This testing level was registered in 2021 with the corresponding number of daily deaths around 0.01 per million (see Fig. 3). Unfortunately, in 2022 the test per case ratio in Japan was the lowest in comparison with 2020 and 2022 (compare brown curves in Fig. 1). Probably, it is the main reason of the highest DCC values in 2022 (compare blue lines in Fig. 1).

The increase of the tests per case ratio needs additional resources, since the number of new cases is very high. Nevertheless, it could be an effective tool to control the SARS-COV-2 infection in Japan and other countries especially now, when the signs of endemic stage this disease have appeared [30].

Conclusions

Non-linear correlation revealed, that the daily number of new cases drastically decreases with the increase of the tests per case ratio.The COVID-19 pandemic dynamics in 2020, 2021 and 2022 has been compared for Japan, Ukraine, USA, and Hong Kong. Some seasonal correlations for Japan were revealed. The presented results indicate that vaccinations do not prevent new infections, but vaccinated persons are less likely to die. Non-linear correlation analysis has revealed the close links between the smoothed daily numbers of new cases and smoothed daily values of the test per case ratio. To decrease the number of new cases and control the pandemic effectively, the tests per case ratio has to be significantly increased.

Declarations

Ethical Approval Statement

No human or animal experiments were used in the study. The statistical information used is public and available on the Internet.

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Author statements

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